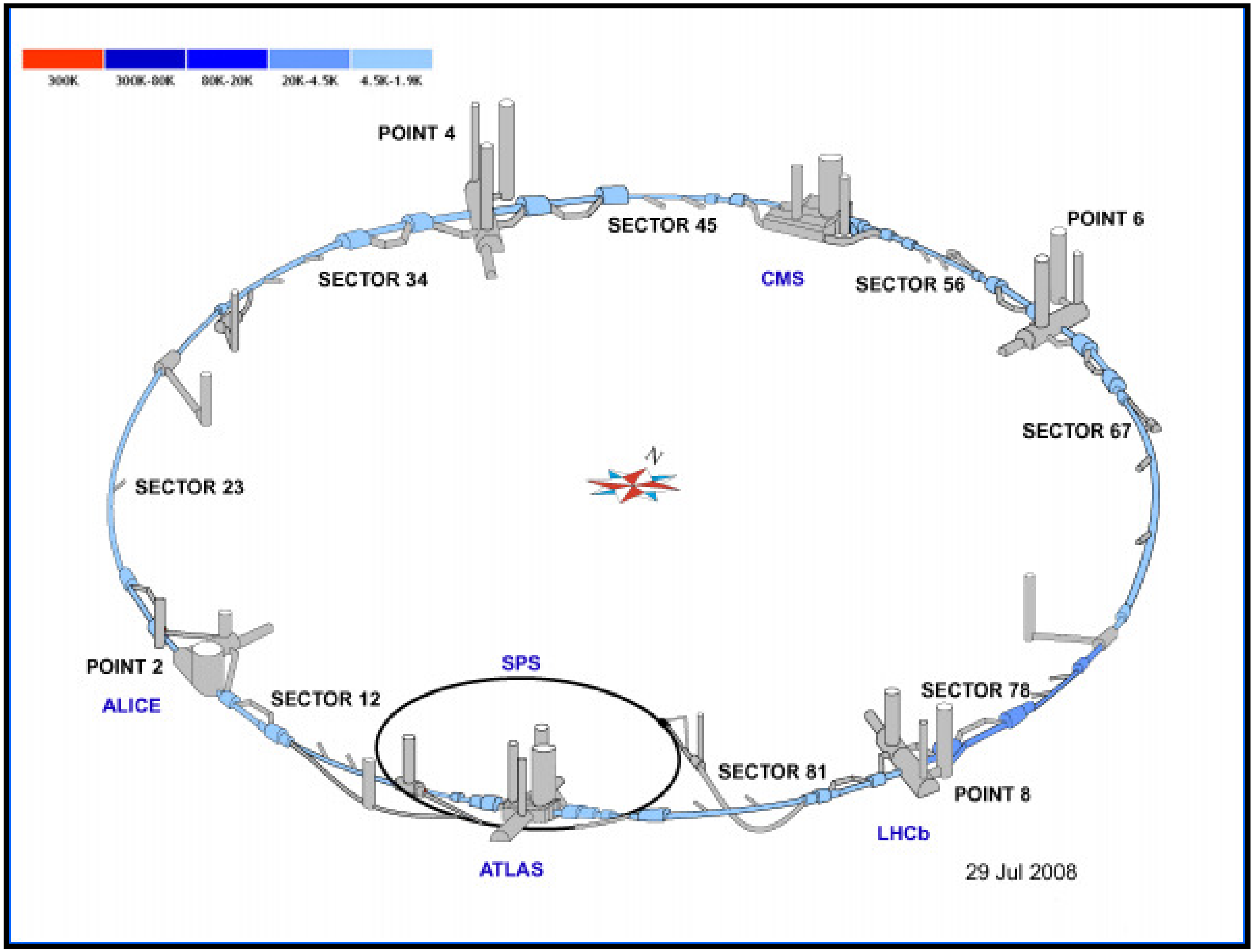
LHC Beam Commissioning and Upgrade Issues: Flat Bunches

Chandra Bhat

LARP Meeting
July 30, 2008

- Purpose of my latest visit to CERN
- Observations on Beam in
  - ❑ SPS Accelerator
    - ➢ During LHC Machine Development studies (and my involvement)
    - ➢ During “Normal” beam operation
  - ❑ PS Accelerator
    - ➢ Glimpse of Various RF manipulations ← Beam preparation
- LHC upgrade issues in a nutshell

CERN Accelerator Complex



Purpose of my latest visit to CERN

- LHC upgrade - Large Piwinski Angle Schemes: One of the upgrade plans at the LHC is to increase the peak luminosity by about a factor of three by using flat bunches (intensity ~5E11/2eVs/bunch) with bunch separation of 50-75 nsec.
  - Discussions with Frank Zimmermann (← Primary Contact Person), Roland Garoby, Elena Shaposhnikova, Oliver Brunning ← (In charge of LHC-LARP activity)

- e-cloud issues: Would like to discuss with experts about simulations and experiments done at CERN on e-cloud issues, e.g., at LHC and other machines like SPS and PS. This will be a topic of interest to us during post collider era for high intensity proton operation of the RR and MI.
  - Discussions with Giovanni Rumolo, Frank Zimmermann (Authors of HEADTAIL/ECLOUD), Benoit Salvant, Mauro Taborelli

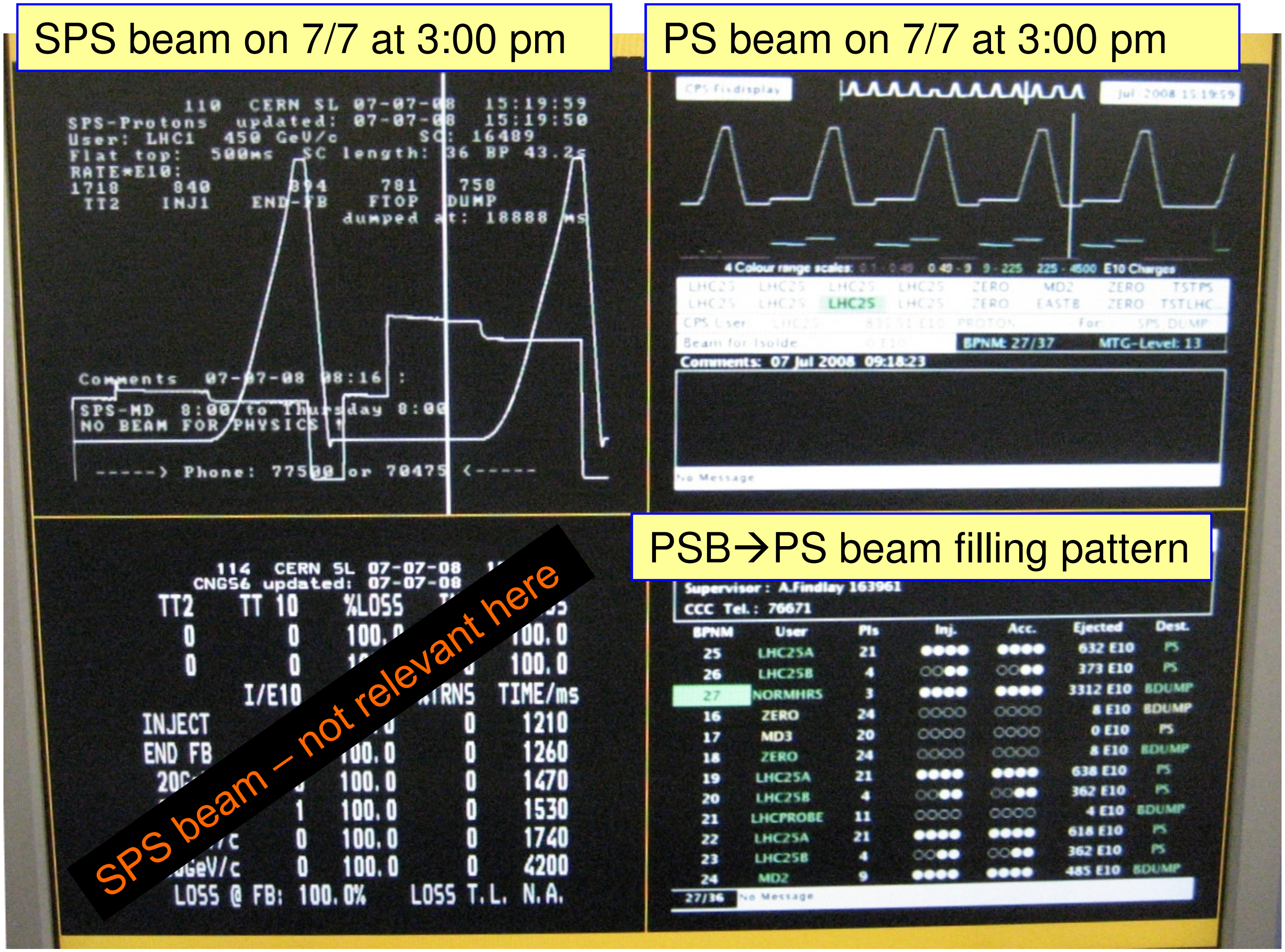
- LHC commissioning:
  Discuss with experts about the issues regarding the initial commissioning of the LHC including upstream accelerators particularly PS and SPS, to identify critical need areas in beam handling, beam manipulation and emittance preservation.
  - Discussions with Gianluigi Arduini (group leader), Elias Metral, (Giovanni Rumolo, Christian Carli)
- Spend some time in the LHC control room during MD studies
  - Elias Metral (LHC injector Coordinator), Gianluigi Arduini, Rene Hazelaar, Jorg Wenninger, Louies

MD Activities

1. **Monday 07/07 (08:00 - ~~16:00~~ 18:00)** - ***Setting-up of the nominal (4 times 72 bunches) 25 ns LHC beam in the SPS (both transverse and longitudinal) until 450 GeV/c*** (OP, RF and ABP)
2. *Monday 07/07 (16:00 - 24:00)* - ***Achieving nominal longitudinal parameters at 450 GeV/c in the SPS*** (T. Bohl)
3. **Tuesday 08/07 (00:00 - ~~08:00~~ 10:00)** - ***e- cloud (build-up & instability) studies in the SPS*** (W.Hofle-E.Mahner-G.Rumolo)
4. *Tuesday 08/07 (08:00 - 16:00)* - ***Rephasing of the LHC beam at flat top in the SPS*** (P. Baudrenghien)
5. *Tuesday 08/07 (16:00 - 24:00)* - ***LHC beam at different intensities with constant longitudinal parameters in the SPS*** (T. Bohl)
6. *Wednesday 09/07 (00:00 - 04:00)* - ***LHC BLM signal at the LHC collimator in the SPS*** (Till Bohlen)
7. *Wednesday 09/07 (04:00 - 08:00)* - ***Test with the radial loop PU in the PS**** (S. Aumon)
8. *Wednesday 09/07 (08:00 - 12:00)* - ***4-ppm power supplies in the PSB injection line*** (K. Hanke)
9. **Wednesday 09/07 (12:00 - ~~20:00~~ 22:00) - *Study of controlled emittance blow-up, reproducibility issue and dependence on 800 MHz settings* (J. Tuckmantel)**
10. *Wednesday 09/07 (20:00) to Thursday 10/07 (04:00)* - ***Long LHC cycle in the PS*** (R. Steerenberg)
11. **Thursday 10/07 (04:00 - ~~08:00~~ 18:00) - *Recovery from MD*** (OP) Change of supercycle: **SFT_LONG-3CNGS-LHCFAST-MD37_V1**

Observations on Beam

(CCC Control Room)



LHC beam: First three batches of beam injection to SPS

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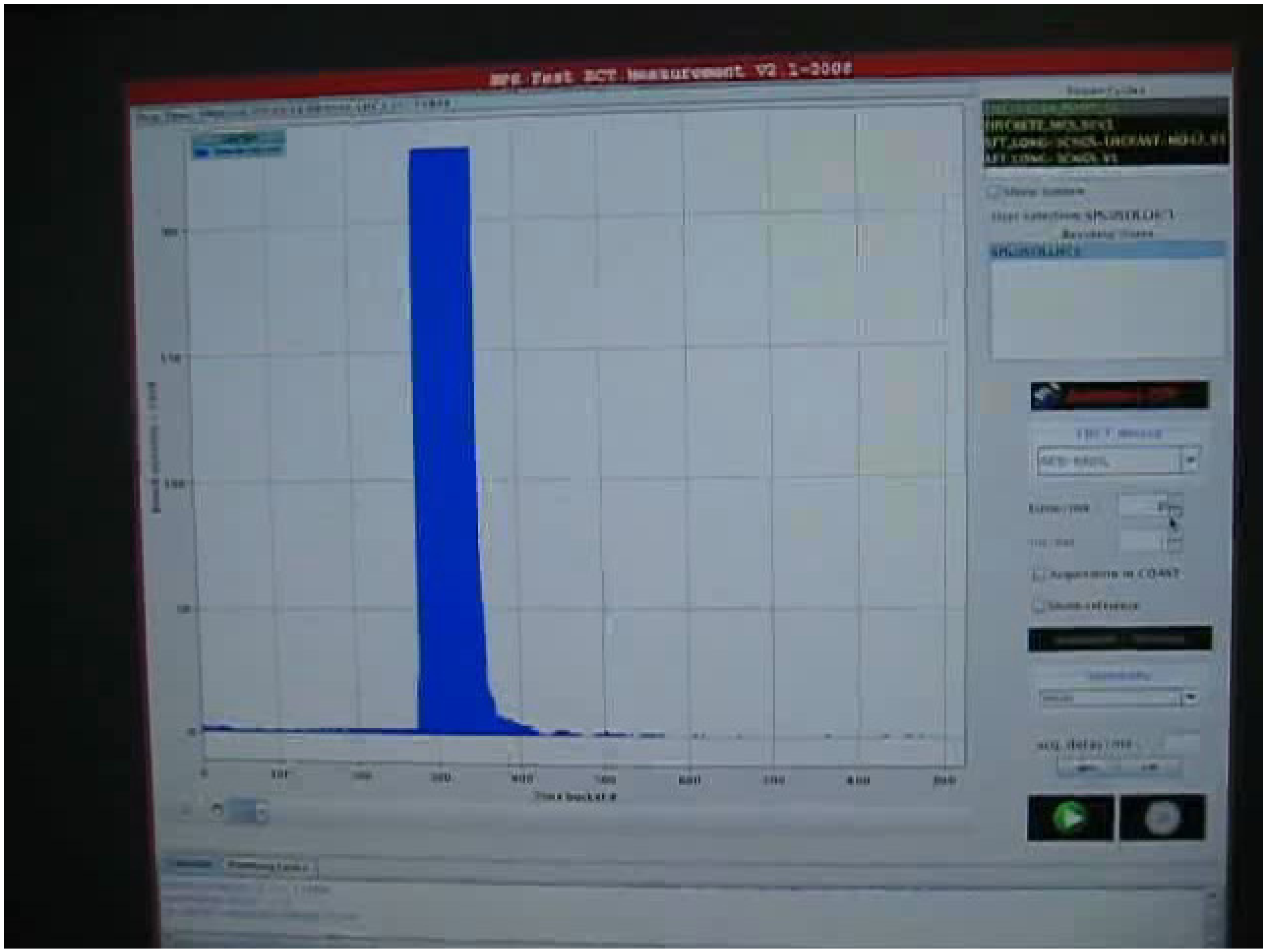
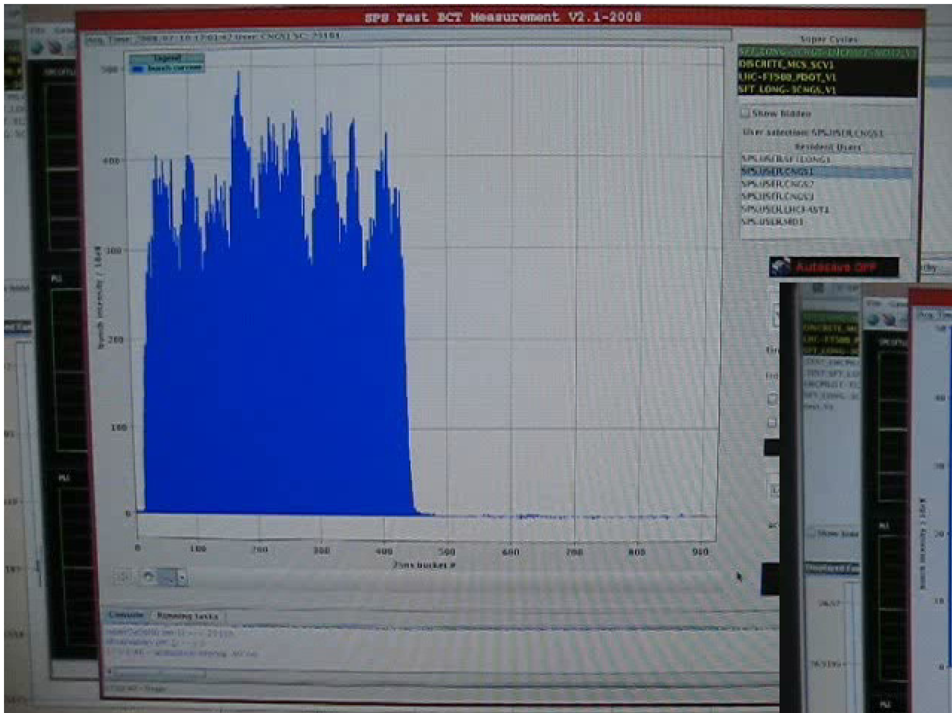
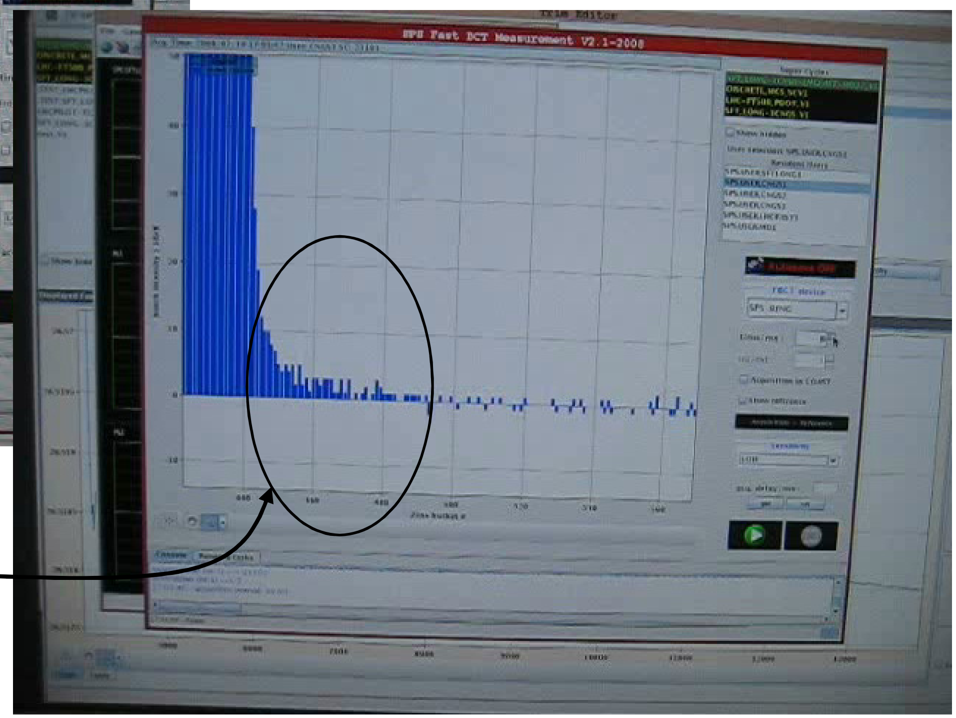


CNGS2 Beam, Normal Operation





Give attention to uncaptured beam

CERN PS Accelerator
(Steven Hancock)

- PS is a machine with a combined function magnets and basic cycle time is 1.2 sec. The PS rf manipulation is quite complicated
  - Primary rf system consists of
    - tunable in the range: 2.8 MHZ-10 MHz
    - 10 +1 rf cavities with 20 kV/cavity,
    - Primarily used for beam acceleration
    - Independently controlled frequencies & Phase
  - f= 13.3 or 20 MHz (Vmax=20 kV), 40 MHz (V=2-360kV), 80 MHz (V<400kV), h=28, 42, 84 and 168
- Cavities are operated in a matrix structure & all the rf manipulation are carried out at a fixed energy –injection, intermediate or final energy porch,

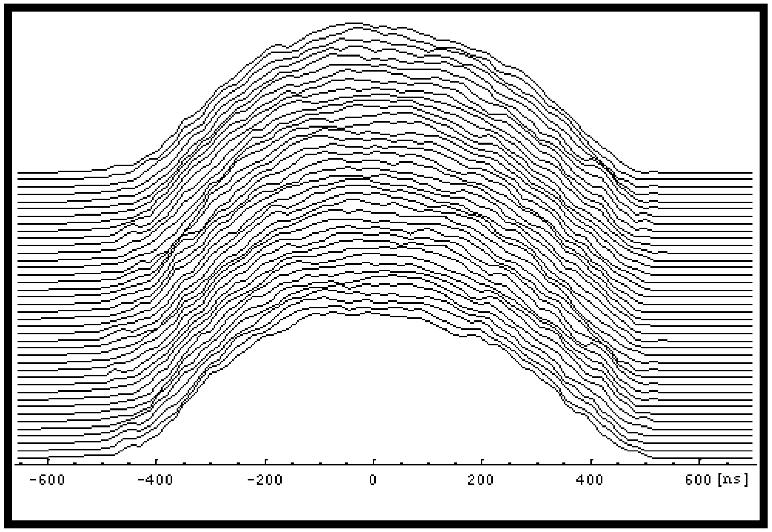
h	1	2	3	4	5	6	7	8	9	10
h1				X	X	X	X			
h2			X					X	X	X
h3	X	X								

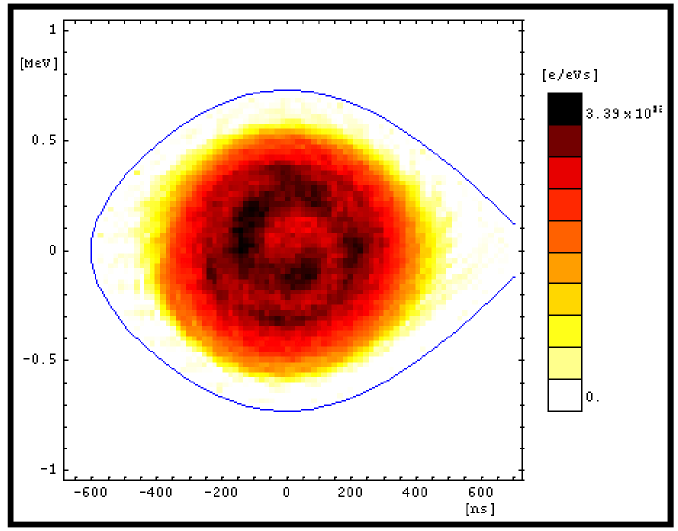
- Example of LHC beam:
  - Start with h=7 (~ 3 MHz). Inject 4+2 bunches, Triple-split with h=7, 14 and 21 ← **18 bunches**
  - Accelerate to 25 GeV and split twice first with h=21 and 42, second with h= 42 and 84 ← **72 bunches**
  - Bunch shortening with h= 84 and 168 systems to achieve 25 nsec bunches to fit into 200MHz buckets after a bunch rotation

Tomography in PS

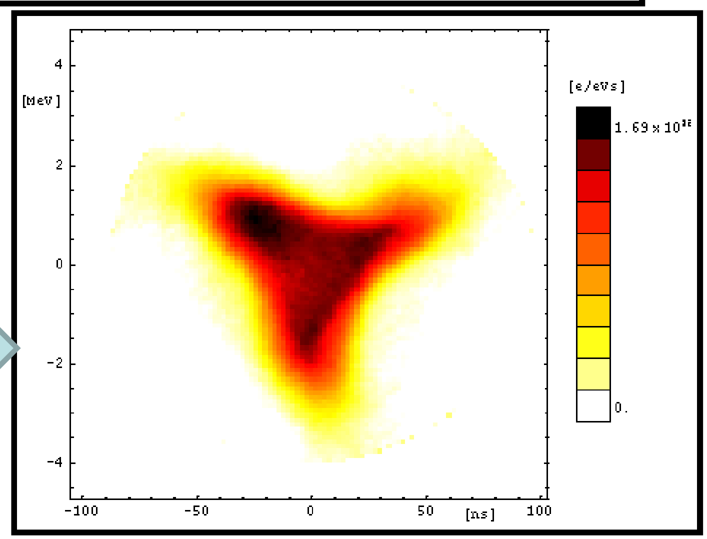
(Steven Hancock)

http://tomograp.home.cern.ch/tomograp/



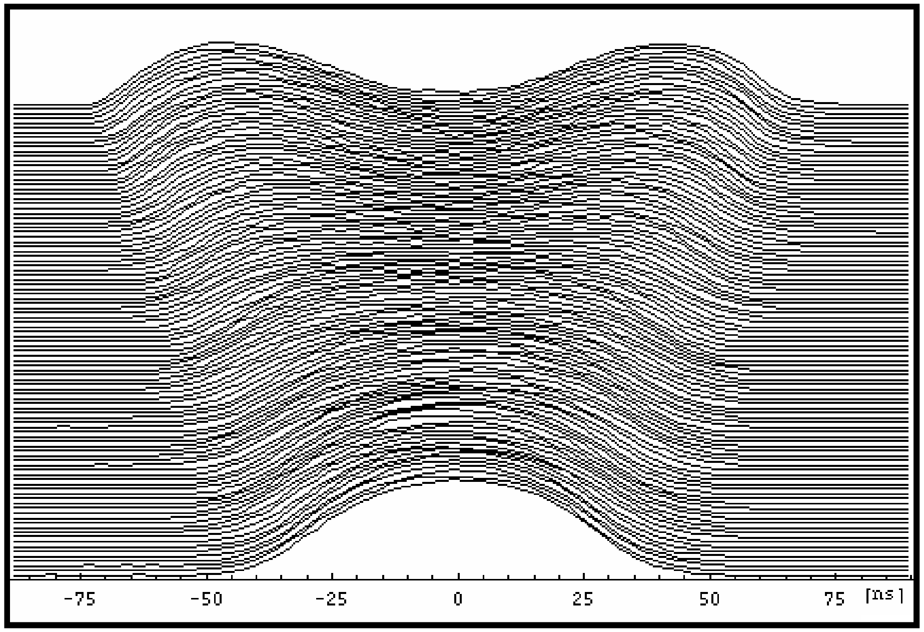


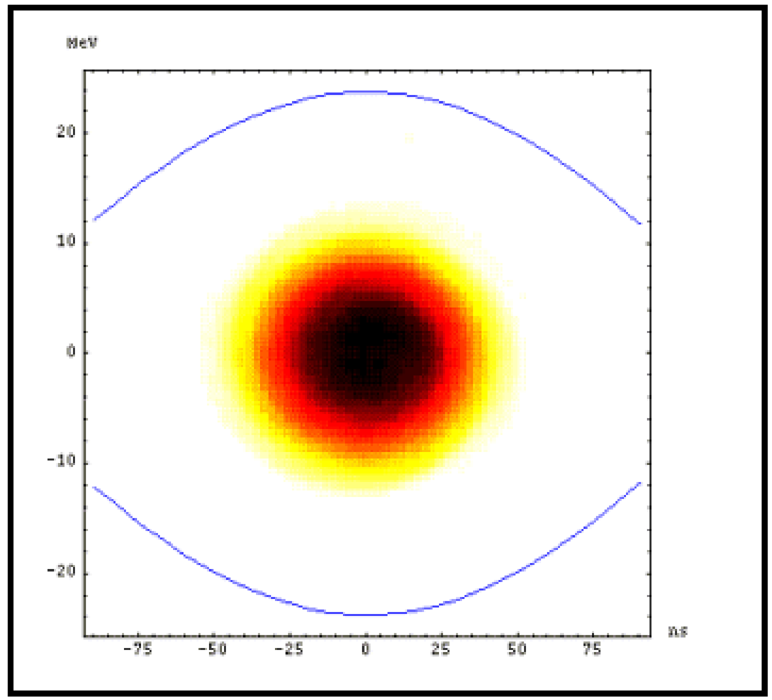
Longitudinal instability seen in the CERN PS towards the end of the beam acceleration



Tomography in PS
(Steven Hancock)

Bunch splitting at 3.5GeV/c in the CERN PS using h=1 and 2





LHC Upgrade: Flat Bunch Scheme

"Scenarios for the LHC Upgrade" W. Scandale, F. Zimmermann, CARE-HHH-APD BEAM'07

Flat bunch Scenario

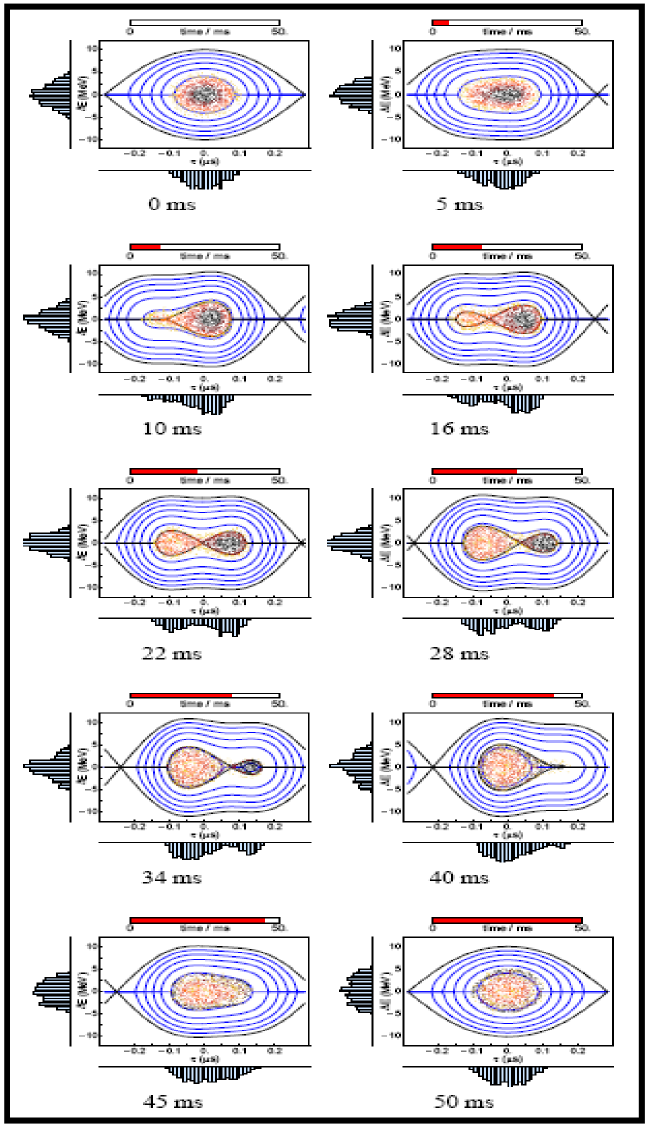
parameter	symbol	nominal	LPA	Tevatron
number of bunches	n_b	2808	1404	
protons per bunch	N_b [10^{11}]	1.15	4.9	~3
bunch spacing	$\Delta t_{\rm sep}$ [ns]	25	50	
average current	I [A]	0.58	1.22	
normalized transverse emittance	$\gamma\epsilon$ [μm]	3.75	3.75	~2.5 33% smaller
longitudinal profile		Gaussian	uniform	
rms bunch length	σ_z [cm]	7.55	11.8	~60
beta function at IP1&5	β^* [m]	0.55	0.25	
(effective) crossing angle	θ_c [μrad]	285	381	
Piwinski angle	$\phi = \frac{\sigma_z}{2\sigma_x^*}\theta_c$	0.4	2.01	
hourglass factor	$F_{\rm hg}$	1.00	0.99	
peak luminosity	$\hat{L}$ [10^{34} cm^{-2}s^{-1}]	1.0	10.6	
events per crossing		19	403	
rms length of luminous region	$\sigma_{\rm lum}$ [mm]	45	37	
initial luminosity lifetime	$\tau_{\rm L}$ [h]	22.2	4.5	
average luminosity ($T_{\rm ta} = 10$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.5	2.5	
optimum run time ($T_{\rm ta} = 10$ h)	$T_{\rm run}$ [h]	21.2	9.5	
average luminosity ($T_{\rm ta} = 5$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.6	3.5	
optimum run time ($T_{\rm ta} = 5$ h)	$T_{\rm run}$ [h]	15.0	6.7	
e-cloud heat load for $\delta_{\max} = 1.4$	$P_{\rm ec}$ [W/m]	1.07	0.4	
e-cloud heat load for $\delta_{\max} = 1.3$	$P_{\rm ec}$ [W/m]	0.44	0.1	
SR heat load	$P_{\rm SR}$ [W/m]	0.17	0.36	
image-current heat load	$P_{\rm ic}$ [W/m]	0.15	0.70	

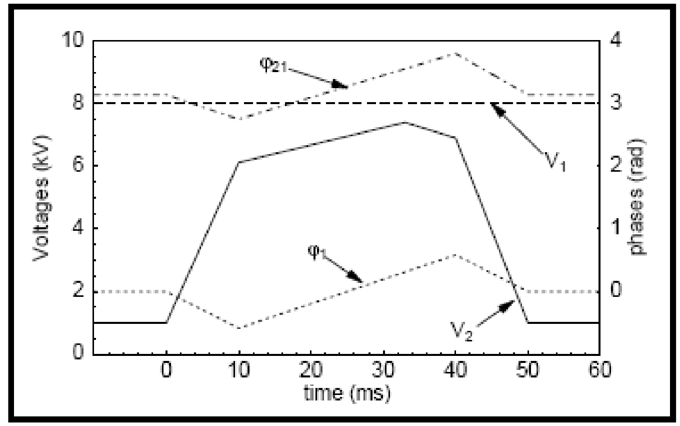
How to produce Flat Bunches

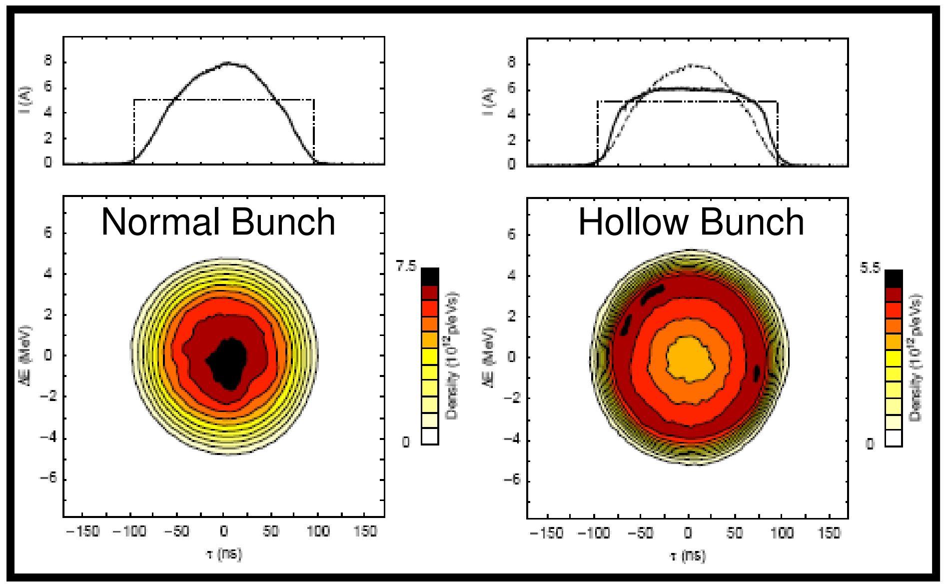
- Several Techniques are available to produce flat bunches
  - 2nd harmonic debuncher in the linac (J.-P. Delahaye et al, 1980)
  - Empty bucket deposition in debunched beam (J.-P. Delahaye et al 1980)
  - Higher harmonic cavity (J.-P.Delahaye et al, 1980)
  - Blow up by modulation near fs together with a higher frequency RF near the harmonic frequency (R. Garoby, S. Hancock, 1994)
  - The recombination with an empty bucket using a double harmonic RF system (C. Carli, M. Chanel, 2001)
  - The redistribution of phase space using a double harmonic RF system (C. Carli, M. Chanel, 2001)
  - RF phase jump (RHIC)
  - Injection of band-limited noise (E. Shaposhnikova).
  - **Barrier bucket**
    - **Wideband rf system**
    - **Resonant rf system with h=1,2 and 4 (a sort of barrier bucket)**

Hollow (flat) bunches with double harmonic rf

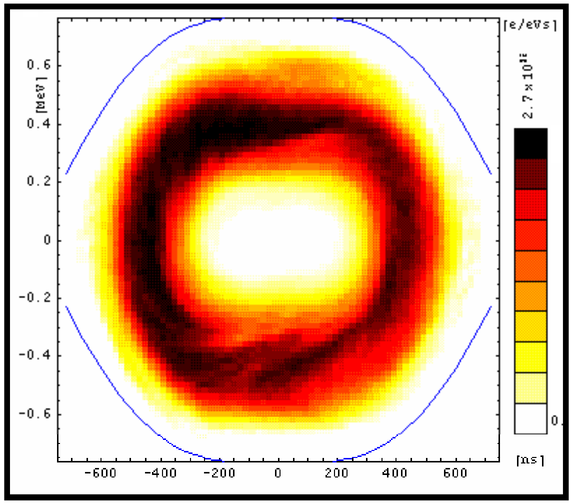
C. Carli, CERN/PS 2001-073 (AE)

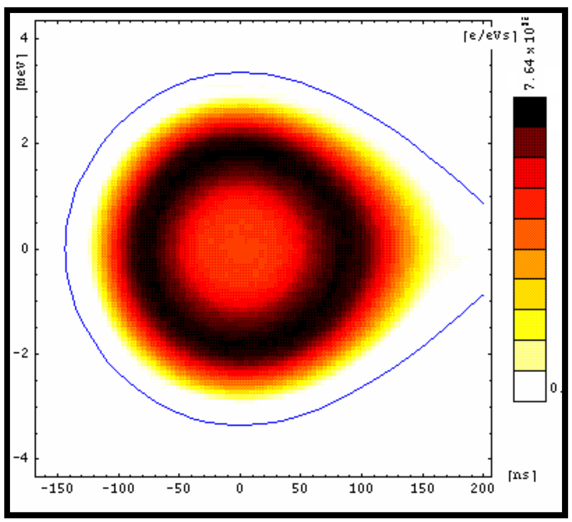






Hollow bunches

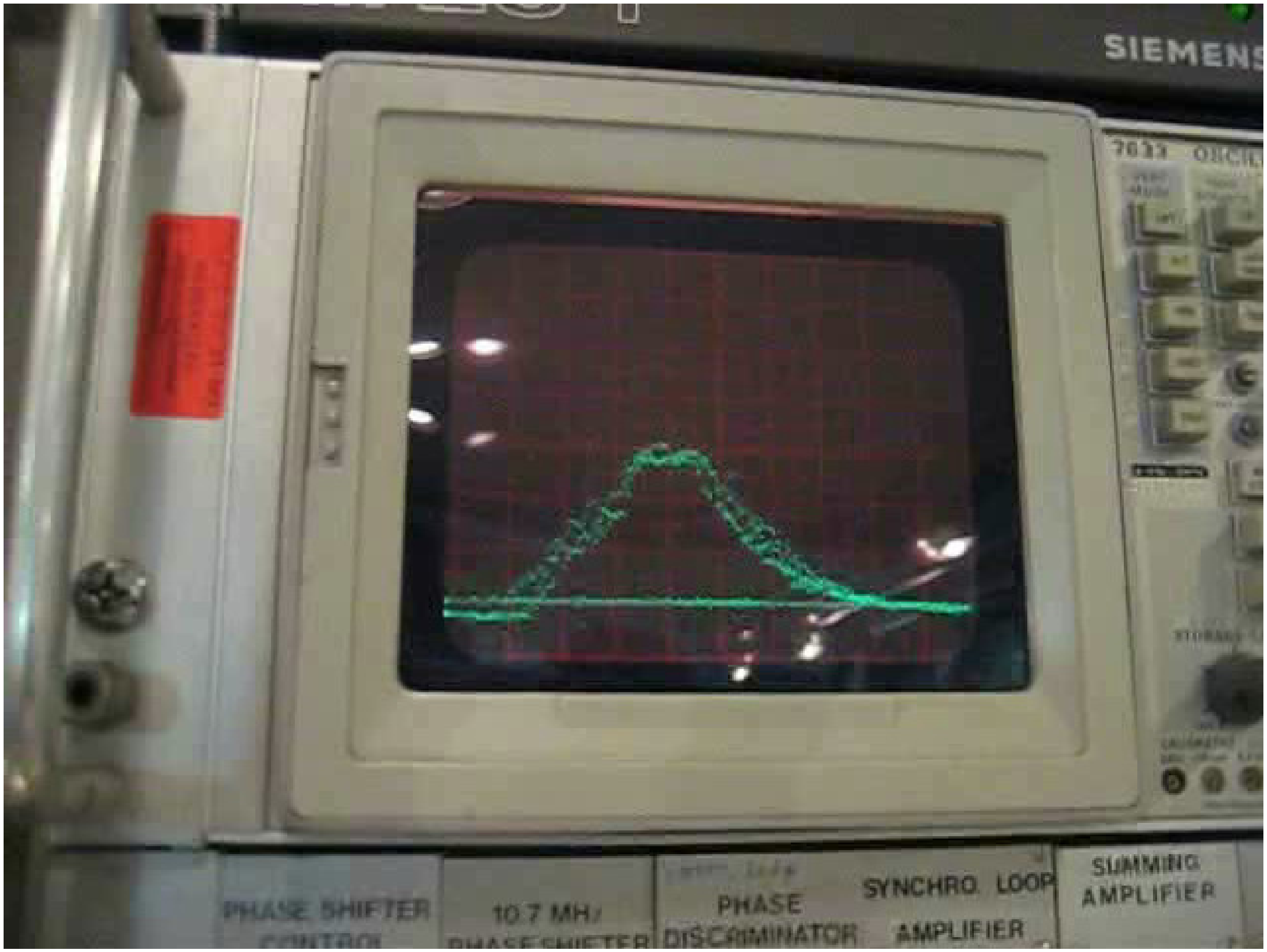




- Completely hollow distribution in a stationary dual-harmonic rf bucket at 100MeV in the CERN PS Booster. Studies carried out in 1998. These bunches are found to be unstable.

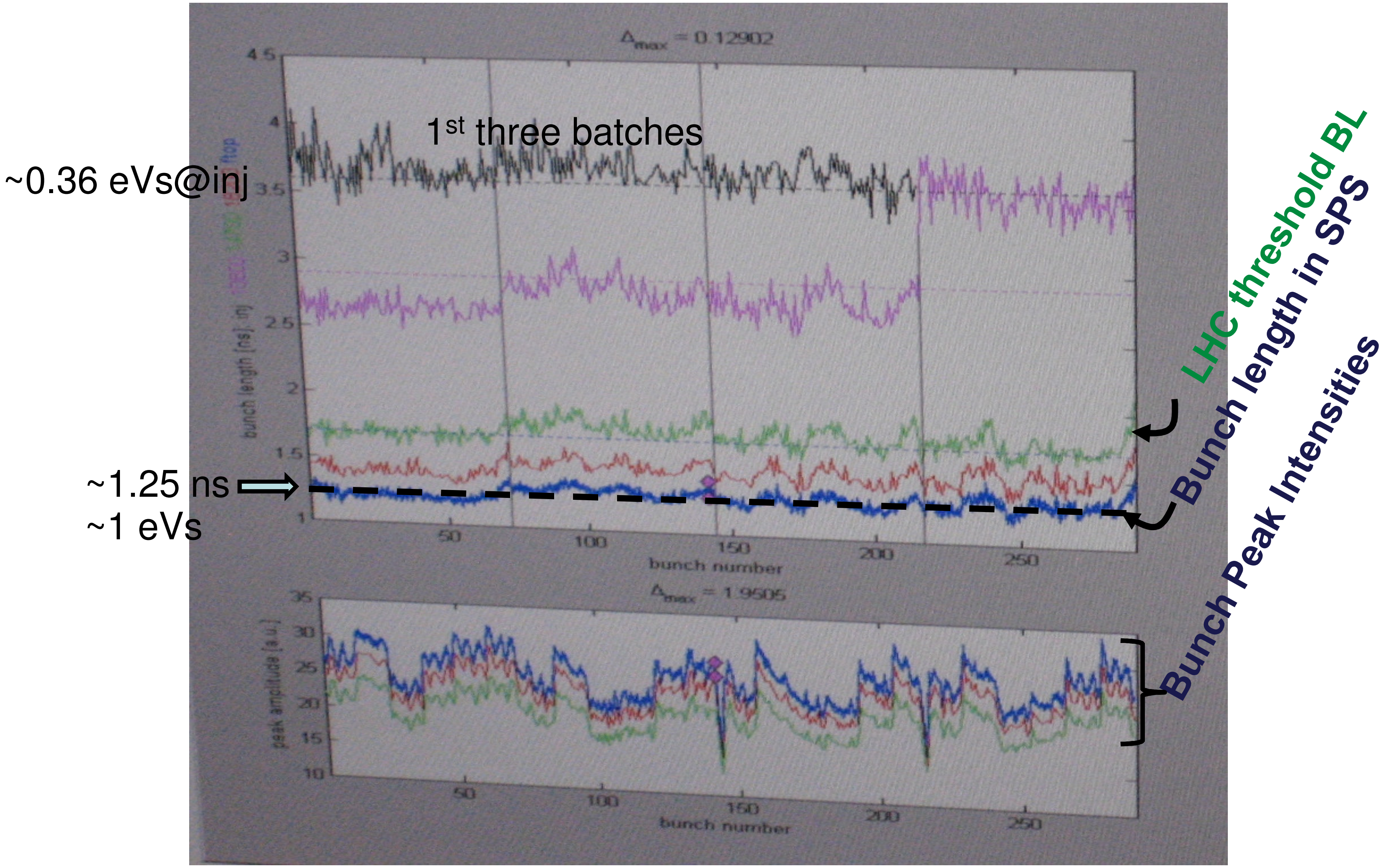
- Hollow longitudinal phase space distribution at full acceleration in the CERN PS Booster. The projected line density is quasi-flat and the bunching factor is significantly improved compared with a typical parabolic bunch.

LHC beam: First three batches of beam injection to SPS



RMS Bunch Length for all 288 bunches in SPS just before injection to LHC

E. Shaposhnikova et. al., 080709

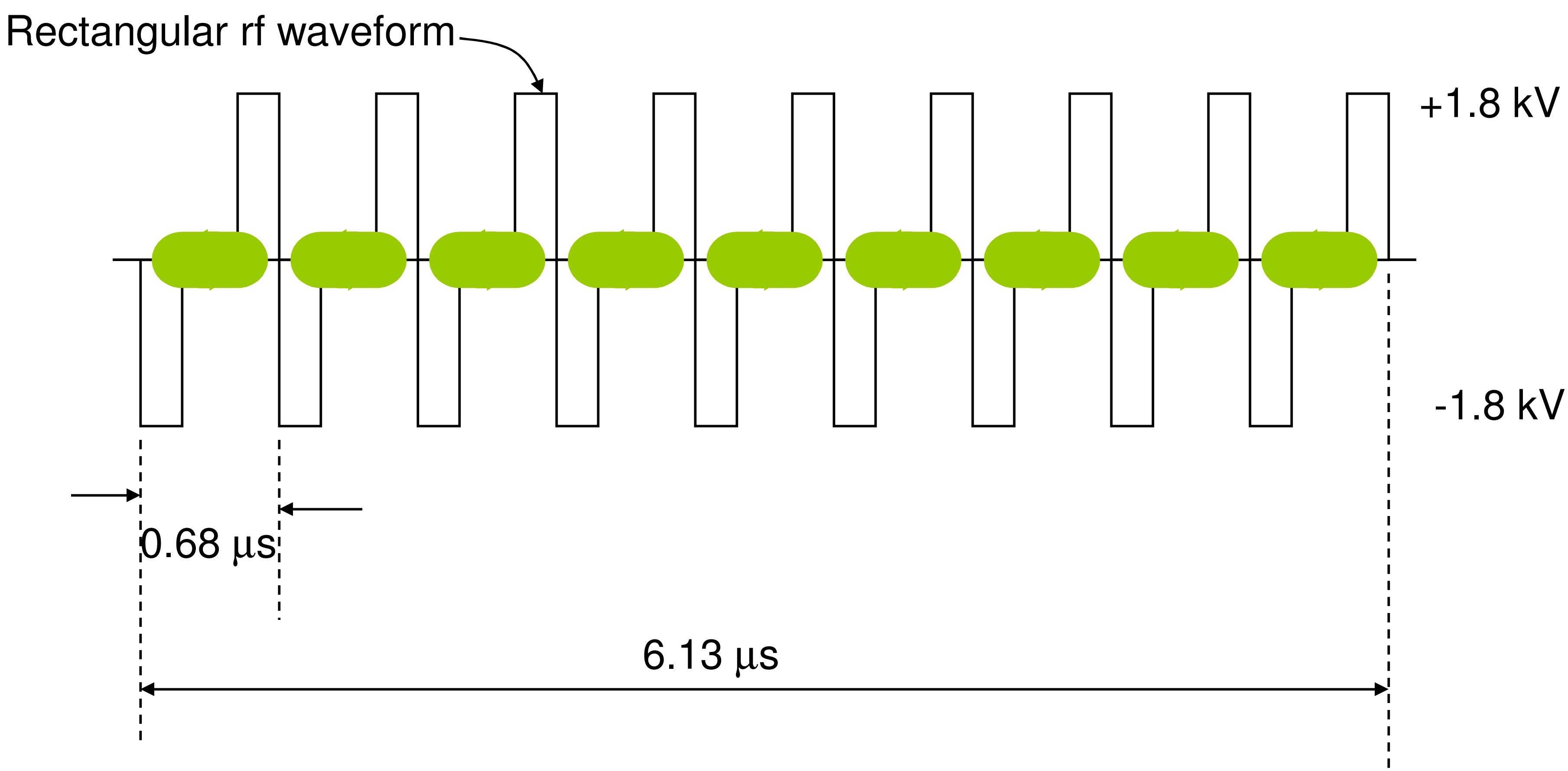


Instability Issues of Flat Bunches

- Landau Damping for a Double RF system (E. Shaposhnikova et. al.)
  - In the bunch lengthening mode and above certain LE bunches become unstable
    - This happens at some critical value of LE the synchrotron tune becomes too large and Landau damping is lost.
    - Experimentally large coherent signals are seen in SPS only if double rf system is active !?! ← **Indicative of above theoretical finding but not conclusive**
    - Giovanni Rumolo(+ his group) are doing some simulation studies with HEADTAIL (modified) of this situation.
- Flat bunches in a single harmonic RF bucket (Frank Zimmermann+ others)
  - Study of Landau damping on an LHC bunch in a single RF system indicated higher stability than another distributions (like Gaussian, parabollic etc.)
- Hollow bunches stored in a single RF in PS showed to become unstable in the presence of RF phase loop (Experiment by Steven Hancock + others)

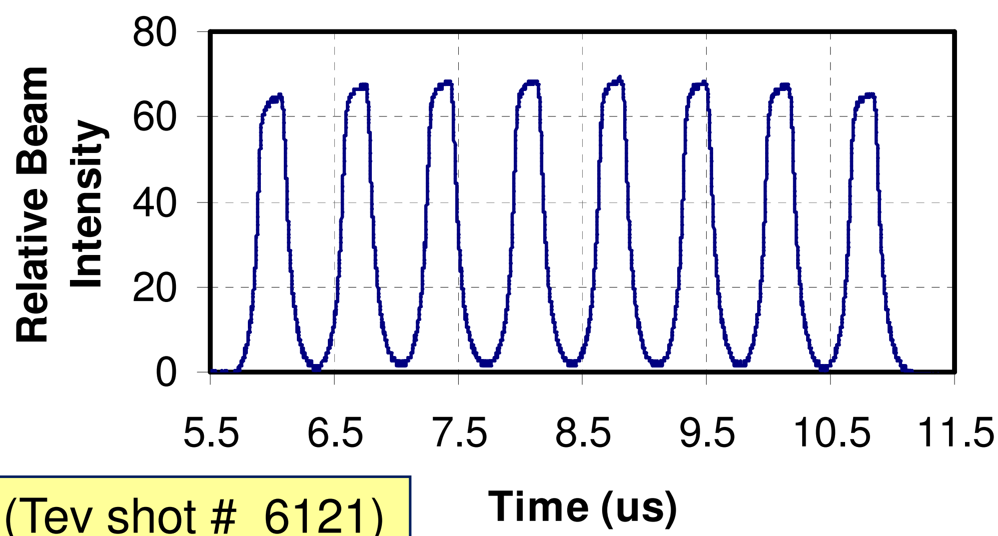
Findings: Studies are inconclusive & Lots of studies are needed

Schematic of the RF profiles for the flat bunches in the RR during momentum mining



Flat Bunches in the RR using barrier RF and extrapolation to to LHC beam

Recycler Bunches Parameters:



(Tev shot # 6121)

Transverse Resistive wall Stability Threshold

$$D \equiv \frac{(N/10^{10})}{4\varepsilon_{||}\,[\mathrm{eV\cdot s}]\cdot 6\varepsilon_{\perp}\,[\mathrm{mm\cdot mrad}]}$$

Intensity = $4.2\mathrm{x}10^{11}$/ bunch
LE(95%) = 5 eVs
$<\varepsilon_T>$(95%) = 2.1 π-mm-mr

(with dampers)

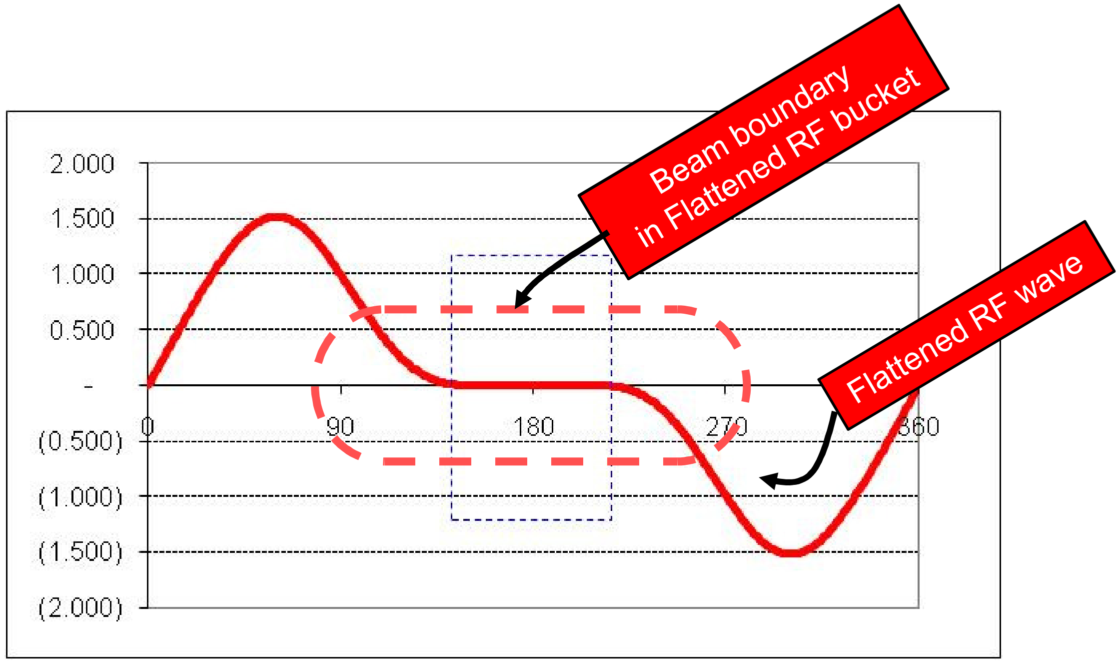
$$D = \frac{Npbar/10^{10}}{<\varepsilon_T(\pi\text{ - mm - mr})>_{95\%}\cdot \mathrm{LE(eVs)}_{95\%}} \approx 4$$

LHC Bunches Parameters:

Intensity = $5\mathrm{x}10^{11}$/ bunch
LE(4σ) = 2.5 eVs
$<\varepsilon_T>$(RMS) = 3.75 π-mm-mr

$$D = \frac{50}{2.5(eVs)\times 3.75\times 6} \approx 0.9$$

A Flat bunch Scenario at LHC



Need H=1, 400MHz, Vrf= 16MV, a= 1
H=2, 800MHz, Vrf= 11MV, b= 0.66
H=4, 1600MHz,Vrf= 1.4MV, c= -.087

Summary & Conclusions

- Spent June 28- July 16 at CERN
- Discussions and worked with PS/SPS/LHC groups
  - Flat bunch scheme for LHC upgrade
  - RF beam gymnastics & Beam Tomography
  - e-cloud: simulation code and experiment, impedance
- Machine Development studies coincided with my visit. It was a fantastic opportunity for me! Participated in beam studies and took data.
- CERN AB group is very much interested in collaborating on these issues and they need help.